

POSSIBLE SOLUTION TO $R_b - R_c$ PROBLEM ¹

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We investigate the R_b - R_c problem, starting from the more difficult R_c . Introducing an isosinglet charge $2/3$ quark Q moves both R_c and R_b in the right direction. If one allows for large c - Q and t - Q mixings, then R_c could be reduced because of singlet content of charm quark, while R_b gets enhanced by a light effective top quark mass in the loop. The heavy quark observed at CDF would be dominantly a singlet quark, while the top quark is lighter than M_W . It is necessary to introduce a second Higgs doublet, where H^+ is heavy while at least one exotic neutral Higgs boson is very light. $H^+ - h^0$ splitting accounts for $\delta\rho$, while light h^0 induce fast $t \rightarrow c + h^0$ decay and hides the actual top quark at the Tevatron. The scenario can be immediately tested at LEP II via search for light top production (and toponium!). At Tevatron, one should search for exotic decay modes such as $Q \rightarrow Z + X$ or $Q \rightarrow H + X$, or measure the BR for the standard bW mode. Light top search should also be renewed.

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1. Introduction

We have heard from Martin¹⁾ and Altarelli²⁾ on the experimental and theoretical aspects of the $R_b - R_c$ problem. Rather than showing the offending “99.9% C.L.” figure, let us give the result from the multiple parameter fit,

$$R_b^{\text{exp}} = 0.2219 \pm 0.0017, \quad R_c^{\text{exp}} = 0.1543 \pm 0.0074, \quad (1)$$

vs. Standard Model (SM) values (for $m_t = 180$ GeV) $R_b^{\text{SM}} = 0.2156$, and $R_c^{\text{SM}} = 0.172$. Thus,

$$\delta R_b \simeq +3.7\sigma, \quad \delta R_c \simeq -2.5\sigma. \quad (2)$$

From both experimental and theoretical considerations, *nobody* seems to like it this way (especially R_c). But, *what if?* We shall give here an *ad hoc* (*à la* Altarelli,) but perhaps natural solution³⁾ that offers absolutely tantalizing phenomenology in the near term.

2. Conservative approach for R_c

Consider the minimal extension of adding just one charge $+2/3$ isosinglet quark Q . One then has new gauge invariant mass terms $\bar{Q}_L Q_R$ and $\bar{Q}_L u_{jR}$, and Yukawa coupling terms $\bar{u}_{iL} Q_R$, where u_i denotes standard up-type quarks. As a result, Q mixes with u , c and t . For sake of discussion, let us ignore 1st generation and set $V_{\text{KM}} \equiv I$ (i.e. discuss only “Cabibbo allowed” modes). One then has the charged current

$$(\bar{c}_L \ \bar{t}_L \ \bar{Q}_L) \begin{pmatrix} C_2 & 0 \\ -S_2 S_3 & C_3 \\ +S_2 C_3 & S_3 \end{pmatrix} \gamma_\mu \begin{pmatrix} s_L \\ b_L \end{pmatrix}, \quad (3)$$

where $S_i \equiv \sin \theta_i$, $C_i \equiv \cos \theta_i$. The isospin part of the neutral current becomes

$$(\bar{c}_L \ \bar{t}_L \ \bar{Q}_L) \begin{bmatrix} C_2^2 & -S_2 C_2 S_3 & +S_2 C_2 C_3 \\ -S_2 C_2 S_3 & C_3^2 + S_2^2 S_3^2 & C_2^2 S_3 C_3 \\ +S_2 C_2 C_3 & C_2^2 S_3 C_3 & S_2^2 C_3^2 + S_3^2 \end{bmatrix} \gamma_\mu \begin{pmatrix} c_L \\ t_L \\ Q_L \end{pmatrix}. \quad (4)$$

One sees that only the $Zc\bar{c}$ coupling is affected at tree level,

$$v_c = \sqrt{\rho} \left[t_3^c C_2^2 - 2Q_c \sin^2 \bar{\theta}_W \right], \quad a_c = \sqrt{\rho} \ t_3^c C_2^2, \quad (5)$$

where $\sqrt{\rho}$ and $\bar{\theta}_W$ are in standard notation. One finds

$$R_\ell \simeq R_\ell^{\text{SM}} \left(1 - 0.41 S_2^2 + 0.30 S_2^4 \right), \quad (6)$$

$$R_b \simeq R_b^{\text{SM}} / \left(1 - 0.41 S_2^2 + 0.30 S_2^4 \right), \quad (7)$$

$$R_c \simeq R_c^{\text{SM}} \left(1 - 2.41 S_2^2 + 1.75 S_2^4 \right) / \left(1 - 0.41 S_2^2 + 0.30 S_2^4 \right). \quad (8)$$

Thus, interestingly, R_c moves down while R_b goes up! However, $R_\ell^{\text{exp}} = 20.788 \pm 0.032$ is a stringent constraint with 0.15% accuracy. Allowing for 2σ variation, and $\alpha_S(m_Z)$ values up to 0.126, taking $m_t = 180$ GeV and varying m_{H^0} between 70 and 300 GeV, we find that higher α_S and lower m_{H^0} values are favored, with S_2^2 varying between 0.007 and 0.009, and δR_c , δR_b between -0.0024 and -0.0032 , 0.0006 and 0.0008 , respectively. The direction is right, but far from sufficient. The reason can be traced to the smallness of $\delta R_\ell^{\text{exp}}$. It would therefore be ideal if one could decrease R_c and increase R_b substantially, but keeping $\delta R_\ell \sim \delta R_\ell^{\text{exp}}$. That is, some fine-tuning is needed between δR_c and δR_b , and eq. (1) is not self-consistent.

In any case, this does not seem to be achievable within minimal extensions of SM, including²⁾ minimal SUSY (MSSM).

3. Radical, Provocative Possibility

Maintaining one singlet quark Q , let us in our minds relax on the requirement on “minimal” extension. One can now decouple the problem from R_ℓ and α_S , since they are not *intrinsically* related to R_b and R_c . Note that Q does not affect ℓ and d sectors directly, and large δR_c is clearly possible, which just means large S_2 . The question now is whether $\delta R_b \sim -\delta R_c$ (so $\delta R_h \approx 0$ is maintained) is possible with just one $Q = 2/3$ singlet quark. It turns out that this in fact occurs *naturally* in the “light, hidden top” scenario of ref. 4, where the top quark (doublet partner of b quark) is light, $m_{H^0} < m_t < M_W$, and the singlet quark Q is the observed heavy quark with $m_Q \simeq 180$ GeV. Here, the light top hides below M_W because of induced $t \rightarrow cH^0$ decay dominating over the standard 3-body $t \rightarrow bW^*$ decay.⁴⁾

The point is that this occurs only if both S_2 and S_3 are large, as can be seen from a formula similar to eq. (4). From eqs. (3) and (4), both t and Q would now enter the $Zb\bar{b}$ loop vertex, since the GIM-breaking c , t and Q mixing modifies the charged and neutral currents. The leading effect can be summarized as a shift to an *effective* top mass,

$$m_t^2 \longrightarrow (m_t^{\text{eff.}})^2 = m_t^2 + 2S_3^2 m_t (m_Q - m_t) + S_3^2 (S_2^2 + S_3^2 - S_2^2 S_3^2) (m_Q - m_t)^2. \quad (9)$$

in the SM $Zb\bar{b}$ vertex. That is, $R_b^{\text{SM}}(m_t)$ in eq. (7) should be replaced by $R_b^{\text{SM}}(m_t^{\text{eff.}})$. Note that it has been known for a long time that the “ R_b problem” itself can be phrased as $R_b^{\text{exp.}}$ favors lighter top quark mass. We find that if $S_2^2 + S_3^2 < 0.5$ and $S_2^2 < S_3^2$, $m_t^{\text{eff.}} < 125$ GeV. We therefore now have a new strategy: large S_2 drives down R_c , while large S_2 and S_3 leads to the light top possibility which drives down R_b indirectly via loop corrections.

As an illustration of this strategy, let us take (in contrast to eq. (1))

$$R_b \simeq 0.2219 \quad (+3.7\sigma \text{ shift}), \quad R_c \simeq 0.1616 \quad (-1.4\sigma \text{ shift}). \quad (10)$$

Thus, with $R_c/R_c^{\text{SM}} \simeq 0.940$, we find from eq. (8) that

$$S_2^2 = 0.0305, \quad (11)$$

which is larger than the values from previous section. Inserting this value of S_2 into eq. (7), we find that $R_b^{\text{SM}}(m_t^{\text{eff.}}) = 0.219$, which implies that $m_t^{\text{eff.}} \simeq 100$ GeV. Taking $m_t = 70$ GeV and $m_Q = 180$ GeV, and solving eq. (9), we get

$$S_3^2 \simeq 0.27, \quad (12)$$

which is larger than S_2^2 . Note that t is still dominantly the $SU(2)$ partner of the b quark, which justifies our flavor label.

4. CAVEATS!

Two problems emerge behind our back at this point. First, a light top and $m_Q \simeq 180$ GeV in the W and Z two-point functions would result in too low a value for $\delta\rho$ (or, insufficient ΔT). In other words, R_ℓ comes back to haunt us in a different way. Second, one can check that the values of S_2 and S_3 from eqs. (11) and (12) are not large enough to support $t \rightarrow cH^0$ decay dominating over $t \rightarrow bW^*$. It is rather amusing, however, that both problems can be removed by the introduction of a second Higgs doublet that does not mix very much with the standard one. All one needs to do is to demand that $m_{H^+} > v$ but $m_{h^0} < M_W$, where h^0 stands for lightest neutral (pseudo)scalar. In fact it is necessary to have m_{h^0} as light as

possible so that $t \rightarrow ch^0$ would not have any phase space suppression. A heavy H^+ does not appear strongly in loop diagrams (such as $b \rightarrow s\gamma$ and B^0 - \bar{B}^0 mixing), but provides a sizable extra ΔT via $H^+ - h^0$ splitting. A very light h^0 is possible if the accompanying nonstandard neutral Higgs is heavier than M_Z . Thus, we find a viable solution to $R_b - R_c$ problem at the cost of introducing an exotic singlet charge 2/3 quark and a second Higgs doublet, with parameters arranged in a rather special “corner”.

5. Phenomenological Discussion

For sake of space, let us summarize the tantalizing phenomenological consequences of this peculiar but not unnatural solution:

- $t \rightarrow ch^0$ is dominant over $t \rightarrow bW^*$ but not overwhelmingly so. Thus, Tevatron should restudy the $m_t < M_W$ region for $\text{BR}(t \rightarrow e\nu + X)$ not much smaller than 1/18.
- The leading Q decays are $Q \rightarrow bW, sW; tH, tZ; cH, cZ$, with relative weights 66.3%, 5.4%, 14.6%, 7.3%, 3.3%, 3.0%, respectively. Thus, more than 70% of Q decays contain W 's, while, since $t \rightarrow cH^0, bW^*$ and $H^0 \rightarrow b\bar{b}$, the b quark content of Q decay is close to unity. Both are in agreement with recent CDF results.⁵⁾
- $\text{BR}(Z \rightarrow t\bar{c} + \bar{t}c) \sim \text{few} \times 10^{-4}$. One should search for the $Z \rightarrow \ell\nu bc$ signal.
- *Dramatic* consequences at LEP-II: TOPONIUM afterall!? Open top could also appear during the LEP 1.6 run next summer, with an extremely light Higgs as a further bonus.

6. Conclusion: We should know within a year, before the $R_b - R_c$ problem itself is settled!

7. References

1. E. Martin, this proceedings.
2. G. Altarelli, this proceedings.
3. For further details and references, see G. Bhattacharyya, G. Branco and W. S. Hou, CERN-TH/95-326 (hep-ph/9512239).
4. W. S. Hou and H. C. Huang, Phys. Rev. D **51**, 5285 (1995).
5. See the talks by T. Liss and T. LeCompte, this proceedings